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Offshore wave power measurements—A review

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ABSTRACT

The first wave power patent was filed in 1799. Since then, hundreds of ideas for extraction of energy from ocean waves have surfaced. In the process of developing a concept, it is important to learn from previous successes and failures, and this is not least important when moving into the ocean. In this paper, a review has been made with the purpose of finding wave power projects that have made ocean trials, and that also have reported what has been measured during the trials, and how it has been measured.

In relation to how many projects have done work on wave power, surprisingly few have reported on such measurements. There can be many reasons for this, but one is likely the great difficulties in working with experiments in an ocean environment. Many of the projects have reported on sensor failures, unforeseen events, and other general problems in making measurements at sea.

The most common site measurement found in this review was wave height. Such measurements was almost universal, although the technologies used differed somewhat. The most common device measurements were electric voltages and/or currents and system pressures (air and water). Device motion and mooring forces were also commonly measured. The motion measurements differed the most between the projects, and many varying methods were used, such as accelerometers, wire sensors, GPS systems, optical systems and echo sounders.

Contents

Abbreviations: AC, alternating current; AWAC, acoustic wave and current sensor; AWS, Archimedes wave swing; BBDB, backward bent duct buoy; DC, direct current; GSM, global system for mobile communications; IPS, interproject service; JAMSTEC, Japan marine science and technology center; (M)OWC, (multiple) oscillating water column; PADA, power analysis and data acquisition; PTO, power take-off; WEC, wave energy converter.

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1. Introduction

The history of wave power research spans over more than two hundred years. The Frenchman Pierre-Simon Girard is recognized as the first holder of a wave power patent in 1799 [1], and since then a great many different other concepts have been conceived. Some of these have come no further than the drawing table, others have made it into small scale models, and a few have also moved on to ocean testing.

Recently de O. Falcão [2] presented a well-written review on wave power research in general and the current status of several of the on-going wave energy projects. In the present review the scope is more limited, and focused on a specific part of offshore or nearshore sea trials, namely measurement systems.

The paper aims at giving a background of how sea trial measurements have been made around the world and consists of a review of wave energy sea trials, where the project developers have also published information of what has been measured. Knowledge of previous measurement efforts, successes and failures may help present and future projects in their sea trial attempts. The information may also be of use in the work with protocols and standards for wave energy development and testing, such as Refs. [3] or [4]. The scope is limited to offshore or nearshore projects, as these bring about different challenges than onshore measurements. Due to the limited space, only schematic explanations of the working principles for the different wave energy converters (WECs) has been included, but the main points should be clear.

Some of the issues of interest within wave power research have also been investigated elsewhere. For example, mooring is perhaps the research area relating to wave energy that has been most thoroughly covered outside the wave energy community. In this paper an attempt to sum up the immense experimental work that has been done on this subject in e.g. the oil or ship industry has not been made. However, the work in Ref. [5] could be mentioned here, since it describes an experimental ocean study that focuses specifically on wave power applications.

2. Typical measurements

Depending on the chosen technology, different parameters are of interest for measurements. Almost all projects have an interest in measuring the incoming waves at the test site. Apart from this, in oscillating water column (OWC) systems, typical measurement entities are pressure and turbine rotational speed. Projects with buoy systems normally have an interest in measuring the motion of the floating body. Overtopping systems have an interest in measuring the water level in the reservoir.

Not all sea trials have included power take-off systems. But for those that have, additional measurements are of interest. For hydraulic systems, oil pressure and pressure differences are typically of interest, as well as generator rotational speed. In linear generator systems, the translator position is generally of interest. For systems that desalinate water, the water flow and pressure differences across membranes can been measured to enable estimations of possible fresh water quantities.

Below, the experiments have been divided into short-term, medium-term and long-term measurements. The first applies to measurements conducted over a few hours or less. Medium-term measurements refer to measurements ongoing for days, and long-term measurements are carried out over weeks, months, or longer.

3. Short-term measurements

3.1. Removable harbors

Klewe reports on experimental tests of a WEC with removable side walls (“harbors”) in the Solent, on the southern coast of UK, in 1984 [6]. The tests were conducted using a 1:10 scale model of a bottom standing OWC system, where power was absorbed using an orifice assembly. The 1:10 scale is based on the test site having waves 1/10 of those typical of the Atlantic. Tests were carried out on a day-trip basis. For each test the model, constructed out of plywood, was towed out to the site and three stabilizing legs were lowered to the sea bed. The depth at the site ranged from 0.6 to 2 m. The model was 1 m wide and the average water column height was in the range 0.5–0.7 m.

Measurements were made of air pressure of each side of the orifice, which had been pre-calibrated so that the air flow could be calculated from data on the pressure drop. Using flow and pressure data, the absorbed power could then be calculated. The measurement frequency was 20 Hz, and each measurement period lasted for 300 s. The sea state was measured about 20 m away from the OWC, using a five point capacitive probe array. This measurement frequency was also 20 Hz.

3.2. Energetech

According to a company report, in October of 2005 the company Energetech tested their full scale (35 m × 35 m × 18 m large, rated at 450 kW [7]) OWC system several hundred meters outside the southern Breakwater of Port Kembla Harbor, on the East coast of Australia [8]. The WEC, which works by focusing waves to a central OWC column, was held in place by two tugboats for a few hours, before being towed back to shore. Electrical power was converted during the experiment, and dissipated into on-board load banks. Though the details of the measurements are not given, the authors list the following measurement parameters: wave height inside the OWC chamber, air velocity, pressures, and power output.

4. Medium-term measurements

4.1. Oregon State University

The wave energy team at Oregon State University conducted a field test of a point absorber WEC named L-10 in October of 2008. The experiment was conducted about 1.5 km west of Agate Beach,

Oregon, USA [9]. L-10 is a dual body system, with a deep draft spar, around which a torus-shaped buoy is allowed to oscillate with the waves. The relative motion between the spar and the buoy is transformed to electricity through a linear generator, where the translator is built into the buoy and the stator is built into the spar. The device tested in 2008 had an outer buoy diameter of 3.5 m, a spar height of 6.6 m, and a rated power of 10 kW.

The ocean test lasted for five days in a range of operating conditions, and several parameters were measured. To measure six degree of freedom buoy motion a system with a triaxial magnetometer, accelerometer, and gyroscope was used. Two magnetostrictive linear position sensors were used to measure relative motion between buoy and spar. Spar temperature and air pressure, as well as battery bus voltages were also measured. This data was wirelessly transfered to a research vessel nearby. To allow for filtering when analyzing the data, the data collection during the ocean testing was over-sampled [9].

For the electric parameters, a special power analysis and data acquisition (PADA) system was designed [10]. This device incorporated a three-phase boost rectifier and a DC–DC buck converter. It measured voltages and currents from the linear generator, and controlled dissipation of the converted electric energy into a fixed resistive load. The PADA system was placed onboard the research vessel, and connected to L-10 through a cable [9]. There was also a relay onboard L-10 that could route the power to a halogen light on top of the spar [11].

Ocean parameters were measured through an acoustic wave and current sensor (AWAC), manufactured by Nortek. The sensor was bottom mounted and consisted of four acoustic Doppler velocimeters for measurements of currents and sea surface displacements. The AWAC system was placed “as close as practically possible” to L-10 [9]. Wave and current measurements were not synchronized with the measurements of device motion in L-10.

5. Long-term measurements

The projects described in this section can roughly be divided into three types. The first five technologies (Kaiyo, Kaimei, the Mighty whale, the Wave dragon, and the Ocean energy buoy) are rather large, articulated floating structures. The Archimedes wave swing, on the other hand, is a bottom standing structure. The last nine technologies (the Isaacs wave-pump, the IPS buoy, the N2 buoy, the Swedish hose-pump, the KN-converter/DWP buoy, the Backward Bent Duct Buoy, the MOWC, the Lysekil project, and Oceantec’s device) are all of the buoy type. Within each group of technologies, the projects have been ordered in relation to when the experiments were conducted.

5.1. *Kaiyo*

A Japanese full-scale experimental plant – “Kaiyo” – was installed about 370 m off Cape of Saba near Iriomote Island, east of Taiwan in August 1984. Kaiyo consisted of an outer structure, 20 m wide and 26 m long, and two inside floaters of breadth 6 m and length 7.25 m. The floaters were allowed to oscillate relative to the outer structure, and through this motion power was transferred via linking arms. The power transmitted from the arms was fed through a hydraulic system, driving a hydraulic motor and a 220 V synchronous generator. A choice could be made between three different motor–generator units: 1 kW, 5 kW or 10 kW. The entire device was mounted on four corner pillars, so that it could be lifted up to approximately 7 m height in bad weather. The water depth at the site was 10 m [12].

Kaiyo was tested for 7–10 days every month starting in August 1984. The experiments were said to be ongoing in Ref. [12], which was published in 1986. Later publications describing the end of the trials have not been found. Several measurements were made onboard Kaiyo and are listed in Table 1. Measurements were made in periods of 10 min. Four technicians were onboard Kaiyo during all measurements. Japanese legislation did not permit automated running of the station. In the summer of 1985, a submarine cable for power transmission was installed at the site [12].

Table 1
Measurements on Kaiyo.

Measurement	Sensor type
Wave height	Water pressure type wave meter
Displacement of actuator piston	Potentiometer
Oil pressure	Pressure transducer
Amount of oil pressure released	Pressure transducer
Output of generator	AC power converter
Surveillance (when jacked-up)	Monitory TV

5.2. *Kaimei*

“Kaimei”, with a number of OWC chambers built into an 80 m long ship-like structure, was a WEC developed by the Japan Marine Science and Technology Center (JAMSTEC) and underwent two rounds of ocean tests. The first round was from July 1978 to April 1979 and is described in Ref. [13]. The second round was from September 1985 to March 1986. A description of this trial is given in Ref. [14]. During both test periods Kaimei was moored northwest of the town of Yura, facing the Sea of Japan, at about 40 m depth. During the first test, Kaimei had 22 OWC rooms connected in pairs, out of which three were equipped with impulse turbines and generators. Measurements were made of incoming waves, power output from the generators, air pressure in the air chambers and mooring forces. The waves were measured through a shipborne wave meter. Generator data was telemetered to a land-based measuring station, but Kaimei was also electrically connected to shore for power transfer [15]. The structure was slack moored at four points in the front and one point in the rear. Mooring forces were measured by Strainstall tension meters [13].

During the second test, Kaimei had 13 air chambers, five of which had been equipped with turbines. Three of the turbines were of the impulse type, one was a Wells turbine and one was a McCormick turbine [14,16]. The Wells turbine was connected to a 60 kW synchronous generator. The impulse turbines were connected to 125 kW induction generators. The McCormick turbine was equipped with a dynamometer. The eight chambers that did not have turbines were equipped with orifices at the top. Four slack front mooring lines and one slack rear mooring line was used. As in the first test period, air pressures, mooring forces and power output were measured. Measurements of vessel motion (heave, pitch and roll) had also been added, but details of the measuring equipment are not listed. Significant wave height was measured by a buoy at the site [14].

5.3. *The Mighty whale*

The “Mighty Whale” is another floating type OWC that was tested by JAMSTEC. A prototype was installed at a depth of 40 m in the mouth of Gokasho Bay, on the southeast coast of Japan, in the summer of 1998 [17,18]. The device was moored using a six mooring lines: four in the front and two in the rear [18]. Test were started in September of 1998, and continued until March 2002 [19]. The Mighty whale was a steel structure with a length of 50 m and a width of 30 m, and it held three air chambers with tandem Wells turbines. Two of the turbines were connected to 30 kW generators and the third one was connected both to a 50 kW generator and

Table 2
Measurements on the Mighty whale.

Measuring parameter	Measuring range	Measuring instrument
Water level inside air chamber	0–12 m	Capacitance type wave height meter
Air pressure inside air chamber	−10–20 mAq	Strain gauge type pressure transducer
Turbine pressure drop	±1.0 mAq	Strain gauge type differential pressure gauge
Turbine torque	±50 kgfm	Electromagnetic type torque detector
Turbine rotational speed	0–3000 rpm	Magnetic type rotational detector
Generated output (generator 1)	0–60 kW	Digital power meter
Generated output (generators 2 and 3)	0–40 kW	Digital power meter
Hull motion	–	Kinematic GPS
Mooring tension	400 ton	Strain gauge type tension meter

From Ref. [18].

a 10 kW generator. Selection of generator was done electronically. All generators were of the squirrel-cage induction type [17].

Measurements were made of several parameters on board, and the Mighty whale was linked to a control station onshore by a telemetry system. The data on minimum, maximum and averages were also saved on a computer on the device, which was unmanned and set to operate automatically. In Table 2, the on board measurement parameters are listed. The measurements of hull motion and mooring tension were not included from the start, but were added later [18]. In addition to these measurements, the wave height was measured, both 100 m in front of the device and 50 m behind it. Two types of wave sensors were used: an ultrasonic wave gauge and a pressure gauge. The data from the pressure gauge was used in rough sea where the ultrasonic gauge could not be used. The measurement frequency for all parameters was 10 Hz [18].

5.4. Wave dragon

Starting in 2003 sea testing was done on a 1:4.5 scale prototype of the Wave dragon. The test were done at a depth of 6 m in Nissum Bredning, a partly shielded bay on the Danish west coast [20,21]. The Wave dragon is a floating overtopping device with two protruding arms to focus the waves to a central ramp. Water that passes over the ramp is stored in a basin, and its potential energy is converted using low-head turbines and generators. With the use of controllable air pockets below the structure, the freeboard of the device can be changed. The tested prototype had seven turbine-generator units and three dummy turbines. It was 57 m wide between the tips of the reflector arms and was rated to 20 kW [22]. Power was delivered to the Danish grid through at three-phase submarine cable, which also was equipped with fiber optics [23].

From October 1st 2004 to January 9th 2005 measurements were made "almost continuously" on the prototype in sample periods of 30 min (corresponding to about 500 waves) [21], with a measuring frequency of 10 Hz [24]. A storm on the 8th of January 2005 led to the failure of one of the force transducers in the mooring, and the device was stranded [21]. In May 2006 the prototype was reinstalled at a site with a more energetic sea state further southeast in the bay and sporadic measurements were made [25]. It is not clear how long this second testing period lasted, but according to the Wave dragon website[1] the device was under repair in May of 2008.

In Ref. [20], measurements made on October 26, 2006 (i.e. during the second test period) are presented. The following entities were measured, at 10 Hz:

- Incoming wave climate: measured at the mooring point, around 60 m ahead of the device, by a pressure transducer approximately 1.5 m below the surface.
- Water level in the reservoir: three pressure transducers mounted to the floor of the reservoir measure the water in the reservoir.
- Crest freeboard: three pressure transducers mounted below the reservoir measure its floating height.
- Turbine outflow: measurements of the rotational speed and the head across a turbine allow calculation of the flow according to the turbine characteristic.
- Inclination of the device: two inclinometers, one for the fore-aft direction and one for the starboard-port direction, were installed on board.

In addition to this, the following measurements from the first testing period have been listed: air pressure in the flotation chambers [24], wind speed, air temperature [23], device motion using accelerometers [26], structural stress, mooring forces and power produced [27]. Structural stress was measured using strain gauges on the bulkheads [23], and strain gauge roses were also installed on the connection between the focusing arms and the main body [21]. Web cameras were used to monitor the behavior of the device [23]. Several filters were applied to the signals described above, e.g. for reducing the effect of cross-basin waves in the signals from the pressure transducers. The parameters and design of these filters are well described in Ref. [20].

5.5. The Ocean energy buoy

A prototype of the Ocean energy buoy was launched in December 2006 in Galway Bay, Ireland. The prototype was of 1:4 scale[2], and is a floating OWC system of the backward bent duct kind. For the first two years, the prototype was only evaluated with respect to sea keeping and mooring loads, but in October of 2008, it was equipped with a turbine and an electrical tower take-off (PTO), as well as measurement systems [28]. The turbine, PTO and measurement system were installed and tested onsite over a period of three days, after which the system was operated until April 2009. Some downtime occurred due to the adjustment of the measurements for machine speed (mentioned below), and some problems due to failures in telemetry. The following measurements were made [28]:

- Electric machine voltage.
- Electric machine current.
- OWC chamber pneumatic pressure.
- Turbine start battery voltage and 24 V service voltage.
- Machine speed.
- Temperature of key components.

The wave height at the site was measured using a directional Waverider buoy, located about 100 m upstream from the WEC. The

[1] www.wavedragon.net, accessed 2010-10-14.

[2] Weighing approximately 28 tonnes according to www.oceanenergy.ie., accessed 2011-04-06.

telemetry system was a combined data acquisition system (with analog to digital cards) which was rack connected to a Linux-based real-time industrial computer. This collated and time stamped the data, and streamed it to shore over a broadband radio link, with a backup GPRS link.[3]

Machine speed was measured with an optical system using a reflective laser sensor mounted in the turbine duct. This sensor had a number of limitations: (i) At low speeds, the resolution became low, as the sensor only gave a signal once every rotation. (ii) At standstill, the measurement could give faulty readings if the reflector was positioned near the laser beam, since vibrations could make the reflector move in/out of the beam. (iii) Sea spray could cause reflections, leading to faulty readings. To remedy these problems, a combination of two measurements was implemented: machine speed was estimated from the machine currents and voltages at low speed, while the laser system was used at high speed. This method is said to have worked “extremely well” [28].

5.6. Archimedes wave swing

In May of 2004, a pilot plant of the Archimedes wave swing (AWS) was deployed 5 km offshore Póvoa de Varzim on the Portuguese north coast [29]. The AWS is a completely submerged system, which utilizes the changes in water pressure as a wave passes over the device. An outer cylinder (floater) moves relative to a bottom standing inner cylinder (silo), and the kinetic energy is converted to electricity using a linear generator. The pilot plant deployed in 2004 had had a floater with a diameter of 9.5 m, a height of 21 m, a rated stroke of 7 m, and a rated maximum power of 2 MW [30,31]. The plant was tested for approximately six months, collecting data for different sea states and using different electrical setups [32]. The plant delivered power to shore through a 6 km long sea cable. In Ref. [33], measurements are presented from two short-term trials when the generator first was connected to a resistive load and then to the grid. The only measured parameter during this test was the load current, which was measured on shore. In Refs. [30,32] some more details are given, and two measurement periods are described (on October 2 and October 3, 2004). The first period was about 15 min long, and the second one about 2.5 min. Three parameters were measured: water pressure on top of the AWS, air pressure inside the AWS, and electrical current on shore. Details of the measuring equipment are not given. Different approaches for characterizing the sea state at the site for the AWS were also reported on in Ref. [31]. The study used three colinear pressure sensors placed on the AWS, together with a Datawell Waverider buoy at a distance from the plant.

5.7. Isaacs wave-pump

Reports on sea trials with an Isaacs wave-pump are given in Refs. [34,35]. The pump consists of a vertical riser with a one-way valve, hanging below a buoy. As the system moves up and down in the waves, the water in the riser is pushed higher and higher, until a sufficiently high pressure is achieved. Two versions of the pump, with 61 m and 92 m risers, were tested in 1972–1973 and 1975. The smaller version was tested off Point Conception and off San Clemente Island, USA. The larger version was tested in the waters near Scripps Institution of Oceanography, San Diego, USA [34]. It was then enlarged for a more thorough testing in Hawaiian waters, about three miles offshore in 1976–1977. The diameter of the float during these tests was 2.4 m. Measurements were made of flow, pressure and acceleration of the float. The flow meter was built especially for the project. The team had also hoped to measure the position of the one-way valve (open/closed) and electrical output. The water-tight compartment holding the electrical components failed however, and the generator corroded. The data was telemetered on command from the float to a shore station [35].

Table 3
Measurements on the IPS buoy [38].

Measurement	Sensor
Piston rod force	Strain gauge based force sensor, placed by the bearing for the generator shaft
Generator rotational speed	Tachogenerator
Vertical motion of the buoy	Accelerometers
Electric voltage	Voltage division on the DC side
Electric current	Current shunt on the DC side
Wave height	Accelerometer mounted inside small buoy, diameter 0.45 m

5.8. The IPS buoy

In 1980 and 1981, a prototype of the Interproject service (IPS) buoy was tested near the lighthouse Trubaduren, outside Gothenburg, Sweden [36,37]. The IPS buoy is a cylindrical buoy with a diameter of 3 m. Below the buoy is a 20 m long open pipe, which also holds a piston. The motion of the buoy sets the water in the pipe in motion, and through the piston rod this motion drives a synchronous generator in the buoy. The power converted in the generator was to be fed to the internal batteries or to a resistive load outside the buoy. The prototype tested had a rated power of 17 kW and the trial went on from September 16th to November 3rd 1980, as well as from June 4th to July 7th and from August 19th to October 26th 1981. It was anchored at three points on 35 m depth. The buoy was equipped to measure the following parameters: surface elevation, buoy acceleration, voltage, electric current, force in the piston rod and rotational speed of the generator [38]. The measurements, and the sensors used, have been listed in Table 3. The wave measurement buoy was placed upstream from the IPS buoy, and was connected to the same mooring [38]. The signals were sent on radio link to a receiver in Långedrag, 17 km away. The system had a capacity to transfer 8 signals simultaneously [36].

During a storm on October 7th 1981, parts of the buoy were destroyed, and it could no longer produce power. It was decided not to interrupt the trial, but instead to install sensors for anchoring forces and utilize the measurement system for this purpose instead. Three force sensors were made using strain gauges and were attached to the anchor lines. Due to a limited amount of bridge amplifiers however, the force measurements could only be combined with either wave measurements or measurements of buoy motion. Wave measurements were chosen as the more relevant, but too large stress broke the sensor halfway through the trial. However, the Swedish Meteorological and Hydrological Institute also made wave measurements nearby (ca 300 m away). These measurements were used in the analysis, but the fact that the measurements were not synchronized put some limits to the conclusions that could be drawn [36]. During the trial in 1981, all of the measurements in Table 3 were made, although not for the entire duration of the trial, as the team experienced some problems with equipment failures. Anchoring forces were not measured. The system was programmed so that measurements were made for 60 min every other hour. During the measurement period the damping was varied automatically between four different values [37].

5.9. N2 buoy

In 1981 and 1982, the wave power buoy “N2” was tested about 100 m from shore in Trondheimsfjorden, west of Trondheim,

[3] The information on wave measurements and telemetry system is not presented in Ref. [28], but has been provided by the authors at request.

Norway. The experiments are thoroughly described in Ref. [39]. A summary is given below. All together, N2 was tested for 114 days during five different periods. N2 consisted of an almost spherical buoy of 1 m diameter, with a rod running through it. The buoy had an opening in the lower end and an inner chamber, meaning that there was a water column inside the buoy. The rod was used for a latching system to lock the buoy in the high and low position. The depth at the test site was 4.6 m at spring ebb and 7.6 m at ebb. A floating platform was placed a few meters from the buoy, and to this platform the cables for measurements were drawn. Cables at the sea bed then connected the platform with a cabin on shore. The cabin held a computer for data logging, phase control and data analysis. For all measurements the sampling frequency was 20 Hz.

Sensors were mounted on the buoy for measurements of buoy position, acceleration, chamber pressure and chamber water level. A potentiometer coupling was used for the measurement of buoy motion along the rod, and an inductive type transducer was used to measure acceleration. The pressure transducer used the same principle as the acceleration transducer. Chamber level was measured using a capacitive transducer consisting of an insulated copper wire as one electrode, and the water itself as the other. The mean of three such wires was used when the buoy tilted. Some problems occurred with fouling of the wires, and also with water sticking to the wire. Power was absorbed as air was pushed through an orifice in the buoy. The air flow as a function of the pressure difference across the orifice was attained through calibration.

At the bottom, where the rod was attached to a gravity anchor, a strain gauge was installed. For parts of the measurement period, strain gauges were also fitted to the roller brackets keeping the buoy on the rod. Wave probes based on pressure transducers were used and mounted on the rod, approximately between 0.8 and 1.8 m below the surface. Two additional pressure probe rigs were placed on either side of the buoy. Each rig was fitted with two probes, to handle the tidal difference. A third wave measurement system was used at a distance from the buoy to measure average wave climate. This system consisted of a pressure transducer hanging under a float, and it required a greater depth to work.

5.10. The Swedish hose-pump

The Swedish hose-pump project made tests both in Lake Lygnern near Gothenburg (1980–1981), and in the ocean outside Gothenburg 1983–1984 [40]. The hose-pump consisted of several floats with damping plates below the water. Between float and plate was a hose, which pumped water as it was elongated and contracted. The hoses were then connected to a common pipe, and water was pumped to shore for conversion using a Pelton turbine and synchronous generator. The demonstration plant of 1983–1984 had three connected converters and was deployed near Vinga lighthouse in Kattegatt. Different buoys, with diameters of 3–4 m were tested, and measurements were made of flow, pressure, and forces on the hose. Measurements of wave conditions were also made. On land, the power produced by the 30 kW generator was monitored [40].

5.11. The KN-converter and the DWP buoy

Over a period of six months in the summer and fall of 1985 (June 3rd to November 5th), Kim Nielsen tested his device – the KN converter – in Øresund, between Sweden and Denmark [41]. The site was situated a few nautical miles south of Elsinore, 500 m east of Espergærde harbor. Similar to the hose-pump system mentioned above, Nielsens system also worked as a water pump. Floats were attached to piston pumps at the the bottom. The pumps fed a common pipe, connected to a submerged turbine and an asynchronous generator. The system tested in Øresund was rated to 1 kW, consisted of four colinear floats, was about 16 m long all in all and was placed at a depth of 5.5 m. On a platform next to the converter, wind speed and direction was measured. Wave elevation was measured with a Waverider buoy, and the water level at the site was also measured. A subsea power cable was drawn to shore, and measurements were made of converted electrical power at 380 V AC. The receiver for the Waverider buoy was placed next to this equipment. The converted energy was fed to the Danish electricity grid [41].

Table 4
Measurements on the DWP buoy.

Measurement	Sensor type
Wave height (outside Hanstholm harbor)	Waverider buoy
Water level, wind speed and wind direction (in Hanstholm)	–
Wire force (above piston, connected through a flexible cable to the seabed structure)	20 ton load cell
Buffer chamber water level	Echo sounder
Buffer chamber air temperature	Temperature sensor
Buffer chamber air pressure	Pressure cell
Piston pump motion	Echo sounder
Piston chamber pressure	Pressure cell
Pressure at seabed	Pressure cell
Vertical vibrations of the seabed structure	Accelerometer

In 1989–1990 and in 1994–1995, a modified version of the system was tested by the Danish wave power (DWP) consortium [42,43]. In this system, a cylindrical buoy was connected to the submerged piston pump. In the 1989 attempt, the buoy had a diameter of 6 m and a height of 1.5 m. The subsea part of the system was installed in November 1989 near Hanstholm in the Danish part of the North Sea, at 5 m depth. The buoy was then connected to the pump on April 23, 1990. Due to a failure of the damping system the end stop of the piston pump was destroyed less than a week later, and the system had to be taken ashore after the buoy had come loose [42]. In the 1994–95 attempt, a smaller buoy with a diameter of 2.5 m was used. It was installed on July 6, 1994, at 25 m depth 2.5 km offshore, outside Hanstholm. This converter was designed to absorb an average maximum power of 1 kW, and had a stroke length of approximately 2 m [43]. The first run of the system went on until September 17 1994, when the buoy sank due to a leakage caused by improper welding. On May 24, 1995, the buoy was reconnected, and the sea trial was said to be ongoing in Ref. [43], which was presented in November 1995. During the sea trial, a number of measurements were made. These have been listed in Table 4. Converted hydraulic power was also calculated, using the measurements of the pressure drop from the piston chamber to the outside, together with knowledge of the effective area of an orifice plate [43].

The sensors and a battery package were connected to a data handler box on the seabed structure. The box was then connected by a 200 m long cable to a data transmitter buoy with a UHF transmission system. The distance from this buoy to the land station at the lighthouse in Hanstholm was approximately 4 km. Data was collected at 4 Hz, for 20 min every 3 h. One month of statistical data was also stored in the memory of the data handler box [43].

5.12. Backward bent duct buoy

Based on a study in the 1960s, Yoshido Masuda developed a small wave power buoy for navigational purposes. The buoy was of the OWC type, with a central vertical pipe for the oscillations. More than a thousand such buoys have come to use in different parts of the world, and thus the buoy is an example of a commercial power plant [15]. From these experiences and using the learnings from the Kaimei project, Masuda later started experiments with a different kind of buoy, with a possibility for much larger scales. The buoy was named Backward bent duct buoy (BBDB) and utilizes an air

chamber bent away from the waves, in which an oscillating water column is induced. Two experiments of about four months each were conducted in 1987 and 1988. The first test was conducted with two different buoys near Yura on the Sea of Japan, from May 21 to September 17, 1987. The buoys were moored by three anchors each at a depth of about 20 m. One of the buoys was a single hull BBDB with an outrigger, about 2.4 m long and 0.6 m wide. The other buoy was a double hull BBDB, about 2.4 m long and 2 m wide. During the test period, the two BBDB systems acted as navigational light buoys. Measurements were made of the electric output of the double hulled buoy using an on-board amp-meter. The meter were checked in intervals of several days. Wave measurements were carried out simultaneously using an ultrasonic type wave probe [15].

The second sea trial took place in Mikawa Bay on the Pacific side of Japan, from March 12th 1988 to the beginning of July the same year. Two different buoys were used during this test also: the double hulled buoy from the first test and a short length center pipe buoy with an underwater plate. The electric output of the double hulled buoy was measured in the same way as in the first test, but there was no wave measurements made during the second test. Instead, wind data from a station nearby was used, and wave data was calculated from wind data using the Darbyshire model [15].

After the two sea trials in the 1980s, further attempts at improving the system was made, and in 1995 and 1996, two more sea trials were made [44]. The first one was made in Mikawa bay on September 11 of 1995, with a cylinder shaped BBDB rated at 300 W, and lasted only a few minutes. A ship remained next to the buoy, and the produced electric current was measured on this ship through a 25 m cable connecting the two. The waves were also measured near the BBDB. In January of 1996, an upscaled version with at 5 kW Wells turbine was tested for a longer time in the semi-open sea south of Guangzhou, west of Hong Kong. This buoy was 6.63 m long, 5.1 m wide and 4.8 m high, and the diameter of the turbine was 0.8 m. It was anchored at 13.6 m depth by a 7 ton concrete anchor. This time, waves were not measured, but estimated to 1–2 m. Electric output was recorded on the buoy from January 17th to February 6th [44]. After this, the recording equipment was stolen, which is quite an extraordinarily unlucky event, even for for a wave power sea trial.

5.13. Multiple oscillating water column

In Refs. [45,46] reports are given on a sea trial of a floating multiple oscillating water column (MOWC) device with four OWC tubes and a generator rated at 5 kW. The device was 15 m high and had an overall diameter of 4.4 m [45]. The sea trial took place from January 16 to February 1, 2001 [46] south of Plymouth Sound, England [45]. A number of measurements are listed, and an analysis of the quality of the measurements is also given in Ref. [46]. The main points from this list and analysis are can be found in Table 5. Measurements were made at 4 Hz and data was recorded for 20 min every 3 h [46]. At the onset of the project, a study of the local wave climate was also made [45].

5.14. The Lysekil project

From 2004 to present, research has been done at Uppsala university regarding a wave power system with a point absorbing buoy connected by a line to a sealed linear generator at the seabed [47]. Several experiments have been made at the Lysekil research site on the Swedish west coast, and a number of parameters have been measured. The Lysekil research site is approximately 2 km from shore, and the depth at the site is 25 m. In Refs. [48,49] measurements of buoy motion and mooring forces are presented from an experiment that was initiated in March 2005 and lasted for a few months. A cylindrical buoy with 3 m diameter was used, with an elastic mooring consisting of two wire sections with a set of six parallel springs in between. The wire was connected to a concrete foundation. A force transducer in a protective casing was attached to the wire between the springs and the buoy, and a triaxial accelerometer was mounted inside the buoy to measure buoy acceleration [48]. The measurements were sampled at 8 Hz, and the signals were transmitted from the buoy to shore through the GSM network [49]. The wave elevation was measured at 2.56 Hz by a Datawell Waverider buoy, located 80 m from the cylindrical buoy [48].

During the spring of 2006, a complete WEC, named L1 and rated at 10 kW was installed at the site. The first data from this system, from March to May of 2006, was presented in Ref. [50]. For the generator, measurements were made of the phase voltages, over resistive loads. The measurements were made onshore, at a measurement station that was connected to the WEC through a 2.9 km long subsea power cable. The sampling frequency was 50 Hz, and the voltage was measured using a 12 bit National Instruments 9201 analog voltage input module and collected using a CompactRIO 9101 and 9002 platform [51]. Later on, current measurements were added in an experiment with a DC load [52]. The current was measured at 50 Hz using LEM current transducers on the AC side and a shunt resistor on the DC side. The measurement frequency on the DC side was varied [53].

Using a separate measurement system, line forces and buoy acceleration for L1 were monitored in the same way as in the 2005 experiment, when the buoy was not connected to a generator [47]. Force was measured using an HBM U5 200 kN force transducer [54].

In the summer of 2008, an optical monitoring system was installed at the site. It consisted of a Sony SNC-RX550 network camera with 26× optical zoom installed at 14 m height on an islet approximately 300 m south of L1. The station was powered by two solar cell panels and a battery pack. The station communicated with shore through a 3G modem, and the transfer rate was 1 image/s [55].

In February–March of 2009, two additional WECs (L2 and L3) were deployed at the site, together with an offshore underwater

Table 5
Measurements on the MOWC device.

Measurement	Sensor	Comments
Individual internal water surface levels	Vega, sonic	Good quality data for two tubes, high noise in two tubes.
Air pressure in OWC tube	Druck, pressure	Good quality data
Temperature in OWC tube	–	Poor quality: sensors proved too slow to respond to the rapid temperature fluctuations.
Atmospheric pressure	Druck, pressure	Good quality data
Generator shaft RPM	Magnetic encoder	Sensor failed to operate
Generator output voltage	–	Sensor failed to operate
Device motion (3 sensors)	Accelerometers	Good quality data, but problematic to analyze entirely due to lack of rate of change sensors
System voltages	Direct voltage	-
Sub sea pressure (3 sensors)	Druck, pressure	Sub sea pressure array not deployed due to adverse weather conditions and loss of device

Modified from Ref. [46].

Table 6
Measurements in the Lysekil project as of summer of 2009.

Measurement entity	Sensor type
Magnetic flux (L2 and L3)	Search coils
Translator position (L2 and L3)	Draw-wire sensor
Generator temperature (L2 and L3)	Integrated-circuit temperature sensor
Substation temperature	Integrated-circuit temperature sensor
Pressure (L2, L3 and substation)	Strain based pressure sensor (failed to operate)
Humidity (L2, L3 and substation)	Integrated-circuit humidity sensor
Water level (L2 and L3)	Resistive sensor
Structure strain (L2)	Resistive strain gauge
Piston/sealing motion and tilt (L2)	Laser sensor
Buoy acceleration	Accelerometers
Buoy tilt	Yaw rate gyro
Buoy motion	Camera on Klammerskär
Line force	Force transducer
Voltage (L1–L3)	Direct measurement
Current (L1–L3)	Hall current transducer

substation. These units had a large amount of measuring equipment installed. In both L2 and L3, sensors were installed to measure pressure, humidity, the position of the translator (i.e. the moving part in the generator), the magnetic flux in the generator and the temperature on the stator [56,57]. The pressure sensor, however, failed to operate. There were also sensors installed to indicate water leakage and subsequent possible water levels inside the casing [58]. In addition to this, L2 was equipped with strain gauges on the inner framework and the inside wall of the capsule, as well as laser displacement sensors to measure horizontal movement and tilt of the seal housing and the piston rod that transfers the line motion to the translator [56]. The translator motion was measured using a Micro Epsilon draw-wire sensor [58]. In the substation, temperature, pressure and humidity was monitored. All signals, including phase voltages and currents from the generators, were sampled in the substation using a CompactRIO platform, before transmission to shore. The substation was connected to shore through a shielded signal cable where four twisted pairs were used [56]. Acceleration and forces on the buoy were measured in the same way as before, but two yaw rate gyros had also been added to measure buoy tilt [58].

All signals from the generators and the substation were sampled at 256 Hz, except for phase currents and voltages. These were sampled at 500 Hz when connected to the substation, and at 256 Hz when connected to dump load. The temperature measurements were multiplexed; every sensor was sampled for one second every eighth second [57]. Measurements in the buoy were sampled at 16 Hz [56]. The measurements above have been summarized in Table 6.

Environmental measurements have also been made at the Lysekil research site. Field sampling of the foundations to determine the abundance of invertebrate assemblages and fish was carried out in 2005, 2006 and 2007. Sessile organisms were documented with under water photographs of 7.0 cm × 10.6 cm areas evenly distributed on the vertical and horizontal sides of the foundations [60]. Similarly sized controls were also conducted 8 m away from the foundations [61]. Fish and crustaceans were recorded through visual censuses on the structures and on the surrounding bottom [62].

5.15. Oceantec

A quarter-scale WEC without power-take off system was tested for roughly a month in the fall of 2008 [63]. The WEC was deployed from mid September to mid October, on the northern coast of Spain between San Sebastian and Pasaia. The site was located about 500 m from shore at about 30 m depth. The prototype consisted of an elongated hull (length 11.25 m, width 1.88 m), in which a number of sensors were installed for measuring mainly the structural behavior and mooring loads. Data communication was handled using a National Instruments Compact Field Point consisting of one module inside the prototype and one module on shore. Communication between the modules was made using wireless modems. The sea state at the site was monitored using three current profilers. Measured entities on the prototype are found in Table 7. Two small wind turbines and some batteries were used to power the instruments.

Table 7
Measurements on the Oceantec WEC.

Measurement	Sensor type
Wave height	Current profiler
Mooring line stress	Load cells
Slamming pressures in the hull	Piezoelectric accelerometers
Hull deformations	Strain gauges
Alarms (temp., humidity, battery level, etc.)	Multiple sensors
Prototype motion (6DOF)	Gyroscopic systems
Prototype positioning and horizontal movements	GPS
Following-up	Argos Radio Beacon

Modified from Ref. [63].

6. Measurements in lakes

Though it its not the main focus of this paper, a few descriptions of experiments in lakes have been published, and are worth mentioning. During the British wave energy program 1975–1982, a number of designs were evaluated and tested to different extent [64]. In Ref. [65], experiments with Salter's duck near the village of Dores in Loch Ness, England, are described. Salter's duck is a wave energy device consisting of several duck-shaped cams rotating on a common spine. Their motion drives hydraulic pumps which are connected to feed a hydraulic motor in a central power unit. During the tests in Loch Ness, measurements were first made on a 50 m long spine with a diameter of 0.91 m, starting in May of 1977 and ongoing for four months. The spine was moored at 22 m depth and was instrumented to measure "structural strain along its length, the pitch, heave and surge dynamics of its ends and the mooring forces". The data was cabled to shore and stored. In parallel to this, wave parameters were measured on a mast fitted with an array of wave height recorders. The mast was placed alongside the device, and its data was also cabled to shore. In December of 1977, another configuration with 20 interconnected ducks was launched and tested for three months. The system could deliver electrical power to a shore-based load, but normally the power was dissipated in relief valves at the hydraulic stage [65]. The measurement parameters during this part of the experiment are not described.

In the 1980s a prototype of the Circular Sea Clam was also tested in Loch Ness [66]. The device consisted of 12 sections with flexible bags, arranged around a circular frame held together with steel spokes. There was no generator on board, instead the power from the varying pressure in each bag was dissipated in air dampers between the sections. The pressure drop across each damper was measured during 6 min tests in varying sea states. The tension in the spoke pointing towards the waves and one spoke perpendicular to the waves was also measured. Similar to the experiments on the Salter's duck, wave parameters were measured on a mast near the test area, using a capacitance type wave gauge [66].

7. Other tests with few details

A number of projects have reported that they have made ocean tests, but have not published descriptions of measurements from these tests. The reasons for this differ in the various projects, but

Table 8
Summary of the reported measurements. Note that several different sensors may have been used to measure the same entity. Projects are in alphabetical order, measurements are ordered with regards to how common they are.

Site data	Number of projects	AWS	BBDB	Energetech	IPS buoy	Isaac's wave pump	Kaimei	Kaiyo	KN-converter/DWP buoy	Lysekil project	Mighty Whale	MOWC	N2 buoy	Ocean Energy Buoy	Oceantec	Oregon State University	Removable harbors	Salter's duck	Sea Clam	Swedish hose pump	Wave Dragon
Surface elevation	18	×	×		×		×	×	×	×	×	×	×	×	×	×	×	×	×	×	×
Wind speed	3		×						×												×
Pressure at seabed	3	×							×			×									
Wind direction	1								×												
Currents (ocean)	1															×					
Air temperature	1																				×
Air pressure	1											×									
Water level	1								×												
Device data																					
Electric power (voltage/current)	14	×	×	×	×		×	×	×	×	×	×		×		×				×	×
Air pressure in device	13	×		×			×		×	×	×	×	×	×		×	×		×		×
Buoy/vessel motion/tilt	11				×	×	×			×	×	×	×		×	×		×			×
Mooring force/tension	9				×		×			×	×		×		×			×		×	×
Water level in device	7			×					×	×	×	×	×								×
Structural stress	6									×			×		×			×	×		×
Device temperature	5								×	×		×		×		×					
Generator/turbine rotational speed	5				×						×	×		×							×
Line or piston force	4				×				×	×			×								
Visual	3							×		×											×
Pressure of working fluid	3					×		×												×	
Piston/translator position/velocity	3							×	×	×											
Relative buoy position	2												×			×					
Turbine torque	2						×				×										
Flow of working fluid	2					×														×	
Slamming pressure	1														×						
Humidity in device	1									×											
Vibrations	1								×												
Magnetic flux	1									×											
Air velocity	1			×																	

possible causes could be: company secrets, shortage of funds for academic work, inadequate data collection for publication, trial failures, a focus on qualitative rather than quantitative results, and so on.

A few projects that have reported on sea trials but have not (yet) described any measurements are the Pelamis [67], Delbuoy [68,69], Buldra test platform [70], the McCabe Wave Pump [71–73], the Ocean Power Technology WEC [74], the Chinese version of the backward bent duct buoy [75], the SEEWEC B1 buoy [76], the Wave plane [77], the Wavepump [78], Wavebob [79], the gyro/flywheel system [80], the AquaBuOY [81], the Oyster [82], the EPAM unit [83], and the Waveroller.[4]

8. Discussion and conclusions

Although wave power sea trials have been performed for several decades, the number of detailed experiment reports remain low. Possible reasons for this were mentioned in Section 7. The measurements reviewed in this paper have been summarized in Table 8. There are several purposes of these measurements. Some measurements are designed to describe the flow and conversion of energy (e.g. surface elevation, voltages, piston force, generator torque, air pressure). Others are used for control purposes (e.g. relative buoy position), and yet others are designed to monitor the general status and condition of the device (e.g. strain, water leakage, temperature).

When studying the material, an obvious conclusion is that it is not trivial to measure any entity at sea. Almost every project that have reported on their measurements have also reported on some kind of problem encountered in the marine environment. For instance, Refs. [41,54] report on broken buoy lines, Refs. [15,31] report on failed deployment attempts, Ref. [22] reports on problems of electrical equipment being exposed to sea spray, Refs. [39,46] report on sensor failures and sensor problems due to biofouling, Ref. [36] reports on the difficulties of adjusting onsite measurements to new conditions, Refs. [9,58] report on the problems of having non-synchronized measurement systems at different locations, and Ref. [28] reports on problems with telemetry. For these reasons, project developers may want to keep the amount of measurement equipment low. The only measurement that is (nearly) universal among the projects is wave height. For this measurement it is for instance possible to install a wave measurement buoy, which is standard system that requires only small adjustments for the chosen site. When it comes to measurements on the device itself, things become more complicated, as there are fewer ready-to-use data collection systems for the specific entities of interest. Electric power and air pressure are the most common entities monitored, and pressure transducers seem to be the most common specific sensor. Device motion and acceleration has also been monitored in many cases, but with very differing methods (e.g. GPS, linear position sensors, accelerometers, optical systems, and echo sounders).

It is clear that although wave power research is far from new, it has not yet matured in a standards sense. Only in one of the reviewed papers [28], which was published in 2011, are there any references to protocols or standards. Likely, this is something which will be more frequent in coming years.

There are 35 years between the earliest and the most recent work referenced in this paper. Over that time, many new technological possibilities have arisen. For instance, the speed at which data can be transmitted and the amount of data that can be stored has increased drastically since the 1970s. So has the opportunities of using satellite systems for positioning and communication. However, these change are noticeable as gradual improvements rather than major revolutions in the referenced projects, and many of the basic methods remain the same over the years. Although different in detail, telemetry was used to communicate wave power measurements in 1973 [34], just as it is used today.

As more and more projects work towards commercialization, it seems reasonable that the number of sea trials will increase. If this will lead to an increase of published descriptions of sea trials remains to be seen.

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